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CAPTIVE-TRAJECTORY STORE-SEPARATION SYSTEM OF THE AEDC-PWT 4-FOOT TRANSONIC TUNNEL

J. P. Christopher and W. E. Carleton

ARO, Inc.

September 1968

PROPULSION WIND TUNNEL FACILITY

ARNOLD ENGINEERING DEVELOPMENT CENTER

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NOTICES

CAPTIVE-TRAJECTORY STORE-SEPARATION SYSTEM

OF THE AEDC-PWT 4-FOOT TRANSONIC TUNNEL

J. P. Christopher and W. E. Carleton

ARO, Inc.

FOREWORD

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This technical report has been reviewed and is approved.

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ABSTRACT

The captive-trajectory store-separation system of the AEDC Aerodynamic Wind Tunnel, Transonic (4T), provides the capability for determining the separation trajectory of a store in the vicinity of the parent aircraft. This system may also be used as a six-degree-of-freedom support for conventional force tests with or without a parent installed, and as a pressure probe or transducer mounting platform for flow field surveys in the vicinity of a model. With the store and parent independently supported in the tunnel, trajectory generation involves measurement of forces and moments acting on the captive store model, converting these to full-scale, adding other forces and moments which may be applied to the full-scale store, solving the equations of motion for store acceleration, integrating these equations to find store displacement, converting this movement to model scale, and physically moving the store model along its flight path. This report describes the captive-trajectory store-separation system and its testing capabilities and presents the technique used for trajectory generation.

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I. ILLUSTRATIONS

NOMENCLATURE

CALCULATED PARAMETERS

C_A	Axial-force coefficient, measured axial force/$q_1 S'$
C_ℓ	Rolling-moment coefficient, measured rolling moment/$q_1 S' b'$
C_m	Pitching-moment coefficient, measured pitching moment/$q_1 S' \bar{c}'$
C_N	Normal-force coefficient, measured normal force/$q_1 S'$
C_n	Yawing-moment coefficient, measured yawing moment/$q_1 S' b'$
C_y	Side-force coefficient, measured side force/$q_1 S''$
F	Force acting along full-scale store body axis (see Fig. 12), lb
i	Integration loop index (0, 1, 2, . . . $\Delta T_p / \Delta t$)
K_A, K_ℓ, etc.	Slope of coefficient-time function; d/dt (C_A), d/dt (C_ℓ), etc., 1/sec
ℓ, m, n	Total moment about full-scale store body x axis, y axis, and z axis, respectively; the positive sense is clockwise as seen from the store center of gravity (see Fig. 12), ft-lb
p, q, r	Full-scale store rotational velocity component about body x axis, y axis, and z axis, respectively; the positive sense is clockwise as seen from the store center of gravity (see Fig. 12), radians/sec
$\dot{p}$, $\dot{q}$, $\dot{r}$	Rotational acceleration components, d/dt (p), etc., radians/sec^2

q_1	Tunnel free-stream dynamic pressure, psf
q_s	Full-scale store dynamic pressure, psf
t	Time from start of trajectory, sec
U	Full-scale store total velocity, ft/sec
U_1	Tunnel free-stream velocity, ft/sec
u, v, w	Full-scale store translational velocity components along body x axis, y axis, and z axis, respectively (see Fig. 12), ft/sec
$\dot{u}, \dot{v}, \dot{w}$	Translational acceleration components, d/dt (u), etc., ft^2/sec^2
W	Full-scale store weight, lb
X, Y, Z	Tunnel coordinate axes or displacement in inches or feet along these axes. As seen by the pilot, the positive sense is ahead, to the right, and down, respectively.
$\dot{X}, \dot{Y}, \dot{Z}$	Full-scale store translational velocity along X axis, Y axis, and Z axis, respectively; ft/sec
x, y, z	Body coordinate axes
ΔT	Step size $(t_p - t_j)$, sec
ν, η, ω	Angular displacement of the store body axis in pitch, yaw, and roll, respectively (see Fig. 11), radians or deg
$\dot{\nu}, \dot{\eta}, \dot{\omega}$	Rotational velocity components, d/dt (ν), etc., radians/sec
$\Delta\nu, \Delta\eta, \Delta\omega$	Angular deflection correction in pitch, yaw, and roll, respectively, deg
ρ_1	Tunnel free-stream density, $slug/ft^3$

CONSTANTS

$a_0, a_1, \ldots, a_5$ $b_0, b_1, \ldots,$ etc.	Coefficients of polynomial fit; lb, lb/sec, ..., lb/sec^5, etc.
a_t, b_t, c_t, d_t	Polynomial cutoff time, sec
b	Full-scale store lateral reference length (span), ft
b'	Store model lateral reference length (span), in.

$C_{\ell p}$	Roll damping coefficient, $\partial C_{\ell}/\partial (pb/2U)$
C_{mq}	Pitch damping coefficient, $\partial C_m/\partial (q\bar{c}/2U)$
C_{nr}	Yaw damping coefficient, $\partial C_n/\partial (rb/2U)$
$\bar{c}$	Full-scale store longitudinal reference length, ft
$\bar{c}'$	Store model longitudinal reference length, in.
d	Roll axis offset distance, in.
I_x, I_y, I_z	Mass moments of inertia about body axis, slug-ft^2
I_{xz}	Cross product of store mass moment of inertia in the body axis x-z plane, slug-ft^2
ℓ_1	Transfer distance; CTS yaw center to reference center-of-gravity location (see Fig. 2), in.
ℓ_{x1}, ℓ_{x2}	Body x axis coordinate of store ejection station, ft
$\bar{m}$	Full-scale store mass, slugs
S	Full-scale store reference area, ft^2
S'	Store model reference area, ft^2
W_X, W_Y, W_Z	Store weight components along tunnel axes, lb
Δt	Integration interval length, sec
λ	Model scale
$\lambda \rho$	Density scaling parameter, simulated density$/\rho_1$

SUBSCRIPTS

i	Current value in integration loop
i-1, i-2	Prior values existing at $(t_i - \Delta t)$ and $(t_i - 2\Delta t)$, respectively
j	Current value at beginning of integration cycle
j-1	Value existing at $(t_j - \Delta T_j)$
p	Predicted value at end of integration cycle
R	CTS rig coordinates
R1	CTS rig coordinates at launch

X, Y, Z	Tunnel axis component
x, y, z	Body axis component
1, 2	Used to denote applied forces

AXIS SYSTEM DEFINITIONS

Body Axis	A right-hand coordinate system with the origin at the store center of gravity; when aligned with earth axis, the store weight vector is along the positive z axis; the positive x direction is toward the nose
Earth Axis	A right-hand coordinate system with the Z axis parallel to the store weight vector; aligned with tunnel axis for simulation of level flight
Tunnel Axis	A right-hand coordinate system with the origin unspecified; the positive X direction is upstream parallel to the tunnel centerline, and the positive Z direction is upward

SECTION I
INTRODUCTION

At the request of the Air Force Armament Laboratory (AFATL), Air Force Systems Command (AFSC), Eglin Air Force Base, the Aerodynamic Wind Tunnel, Transonic (4T), of the Propulsion Wind Tunnel Facility (PWT) was provided with a Captive-Trajectory Store-Separation System (CTS) to conduct studies on the flight behavior of various store models launched from parent aircraft.

The purpose of this report is to describe the CTS hardware, the closed-loop position control using a digital computer, and the six-degree-of-freedom equations of motion used in the computer program. Although several wind tunnels in the United States have the CTS test capability, each of these generate the store trajectory either with an analog computer which requires a long test set-up time or by open-loop digital calculations which require a long tunnel testing time. The closed-loop digital computer system of Tunnel 4T has greatly enhanced the production of trajectory data.

SECTION II
APPARATUS

2.1 TEST FACILITY

Tunnel 4T is a variable density, closed-circuit, continuous flow wind tunnel capable of operation at Mach numbers from 0.10 to 1.40 and a stagnation pressure range from 300 to 3700 psfa. The tunnel is located within the quadrangle of the PWT 16-ft supersonic tunnel (Aerodynamic Wind Tunnel, Hypersonic (16S)), Fig. 1, Appendix I, and is powered by the PWT Plenum Evacuation System (PES) compressors. Tunnel operation is conducted from a control console located in the control room of the 16-ft supersonic tunnel. The test section is 4 ft square by 12.5 ft long with variable-porosity walls ranging from 0.5 to 6.0 percent open. A schematic of the tunnel test section showing the installation of the captive-trajectory system and a store model is presented in Fig. 2. An isometric drawing of the tunnel arrangement with the cover building removed is presented in Fig. 3 and depicts a parent aircraft model on the Tunnel 4T model pitch support sector. A typical CTS test installation is shown in Fig. 4. The pitch support is remotely controlled and has an angle-of-attack range from -12 to 28 deg. The sector and boom of the pitch support are retractable from the airstream to facilitate tests of models not using the system. A more detailed description of the tunnel and support equipment may be found in Ref. 1.

2.2 CAPTIVE-TRAJECTORY STORE-SEPARATION SYSTEM

2.2.1 General

The CTS is used primarily for the trajectory analysis of air-launched stores and, in effect, is a separation simulator which uses the tunnel as a six-degree-of-freedom function generator for the aerodynamic coefficients of the store. The CTS hardware consists of a six-degree-of-freedom store model support with a closed-loop, analog-control positioning system for each degree of freedom and interface equipment to provide communications with the PWT Raytheon 520 digital computer. The CTS model support and positioning systems were designed and built by General Dynamics, Convair Division. The interface hardware and the software required for trajectory generation and data reduction were developed by the PWT Instrumentation Branch.

2.2.2 Store Model Support

The CTS store model support, Fig. 5, is an electromechanical system with six degrees of freedom. All axes of motion are contained within a single mechanism that is independent of the parent model support. Drive motors located in a housing attached to the tunnel structure above the tunnel diffuser are printed-circuit-armature, DC electric motors with extremely fast response. The motors will come up to speed in approximately 0.1 sec. The motors for axial and vertical motion are rated at 780 in.-oz of torque at a speed of 1060 rpm. For pitch, yaw, roll, and transverse horizontal motion, the motors are rated at 120 in.-oz of torque at a maximum speed of 2750 rpm. Resulting maximum linear and angular velocities of the six degrees of freedom are as follows:

Attitude	Maximum Velocity
X, axial	1.7 in./sec
Y, horizontal	5.2 in./sec
Z, vertical	1.3 in./sec
ν, pitch	20.7 deg/sec
η, yaw	20.7 deg/sec
ω, roll	55.0 deg/sec

During tests involving store model separation from a parent aircraft, the horizontal, pitch, and yaw maximum velocities are reduced by a factor of ten to minimize overtravel in the event of parent-store fouling (see Section 2.2.5).

The axial, vertical, and horizontal motions are accomplished by driving ball screws. The envelope of translation of the support head is

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±15 in. away from the tunnel centerline in the transverse horizontal and vertical directions. The axial range is ±18 in. from a reference pitch axis location at tunnel station 133.25, see Fig. 2. Pitch and yaw motions are accomplished by driving the respective gear sector with a conical worm gear located in the head of the support. The maximum angular range of pitch and yaw motion is ±45 deg. A schematic showing the normal and offset roll shaft provisions of the CTS support head is shown in Fig. 6. The normal roll shaft is driven by an eccentric gear reduction drive with a maximum angular motion of ±360 deg and has provisions for installing either an adapter for a model support sting or an adapter with a chain sprocket for driving the offset roll shaft. The offset roll shaft has provisions for mounting a model support sting and has the same maximum angular motion as the normal roll shaft.

The axial and vertical motors are connected to their respective ball screws by timing belts. Power for transverse horizontal motion, pitch, yaw, and roll is transmitted to the support head by flexible shafts. Position readout for each degree of freedom is accomplished by the use of precision rotary potentiometers which are driven with a minimum gear reduction between the motion gear and the potentiometer.

2.2.3 Position Control

A schematic of the CTS control system is shown in Fig. 7. Signal conditioning equipment and position control and monitoring equipment are located on the CTS control console depicted in Fig. 8. The control console is located in an instrument room adjacent to the tunnel. The position indicators and the components of the control panel except the manual positioning potentiometers and override switches depicted in Fig. 8 are duplicated on a panel of the Tunnel 4T control console for monitoring purposes. The 4T control console panel also contains command switches, Fig. 9, to the computer for initiating and stopping a trajectory and controlling output trajectory data from the computer. In computer-controlled operation, the CTS position command signals are applied to the summing junctions of operational amplifiers, Fig. 7, by digital-to-analog converters (DAC) which are controlled and updated by the computer. For manual operation the DAC inputs are replaced by potentiometers for manually positioning the CTS. The controllers respond to the difference between commanded and actual rig positions as computed by the operational amplifiers and drive printed circuit motors through silicon-controlled rectifier (SCR) bridge circuits. Back-emf of the motors, sampled when the SCR bridges are turned off, provides velocity feedback. Motor velocity is proportional to the position error with maximum speed obtained for a 4-percent error. The threshold for

movement corresponds to an error signal of less than 0.05 percent. The controllers provide motor overload protection by electronically limiting the drive currents.

For any axis the overall positioning error including effects of rig misalignment, potentiometer nonlinearity, backlash, power supply drift, and other error sources is less than 0.2 percent of full-scale travel.

2.2.4 CTS-Computer Interface

The large data processing system of the 16-ft supersonic tunnel is available for Tunnel 4T use. In addition, a 16-channel system is part of the CTS. Six channels are for rig position inputs to the computer, and 10 channels are for force data including the model balance measurements. The data signals are amplified as required, filtered by 2-Hz low-pass filters to remove noise, and fed through a commutator and analog-to-digital converter (ADC) into the normal 16-ft supersonic tunnel data acquisition system. Upon initiation of a data acquisition cycle, CTS data, along with tunnel flow condition data pertinent to the test, are read into the computer; the computer performs the prescribed calculations and concludes the cycle by setting new positions into each DAC. At the conclusion of rig movement, another cycle is automatically initiated.

2.2.5 Safety Provisions

For overtravel protection, a dual limit switch is provided in each direction for each degree of freedom. If the first limit is exceeded, a controller safety circuit is activated which applies dynamic braking to stop the motor. This limit can be overridden to return to a safe position. If a backup limit is exceeded, the motor controller power is shut off, and the motor must be manually cranked back into the operating range.

Protection against a damaging store-parent collision is also provided by electrically isolating the store from the remainder of the support system. In the event the store contacts the parent, a "ground" is detected and the controller safety circuit is activated.

Additional protection is provided by mechanical brakes which are actuated to prevent vertical or axial movement in case of a power failure. Brakes are not required for the other degrees of freedom since the loads are not large enough to overcome the friction of the drive train.

Television monitors located in the Tunnel 4T instrument room and on the Tunnel 4T control console are used for visual observation during movement of the store to the starting position and during the controlled positioning of the store in the trajectory. For a trajectory starting from the launch position, parent-mounted touch wires provide a remote indication of the rack position.

SECTION III
TRAJECTORY GENERATOR

3.1 GENERAL

The primary capability of the CTS is the generation of the store flight path in the vicinity of the parent aircraft. For this type of testing, the parent aircraft model is sting mounted in the tunnel test section at the desired angle of attack utilizing the Tunnel 4T pitch sector. The instrumented store model, mounted on the CTS rig, is removed a safe distance from the parent until tunnel conditions are established. For a trajectory starting from the launch position, the store is moved manually to the parent-store mate position (see Fig. 4). This launch position is the reference point from which store movement with respect to the parent is measured. On the first data point, the DAC's are set to correspond to this touch position. The positioning system input can then be switched to computer control and the trajectory started.

To begin a trajectory at other than the launch position, it is only necessary to specify the coordinates of the starting point referenced to the touch position and the store velocity components at this point.

The technique of trajectory generation is illustrated by the flow diagram presented in Fig. 10. The trajectory calculations can be logically divided into aerodynamic coefficient determination, coefficient prediction, solution of full-scale force and moment equations, and output calculations. Apart from these trajectory calculations, the computer program also includes auxiliary calculations to produce the trajectory data in the format desired for the particular test.

Upon completion of a computation cycle, the rig moves to a new position and logic circuitry outside the computer initiates another cycle. The total time for a complete cycle is between 3 and 6 sec. The time required for a complete trajectory encompassing one-fourth to one second of actual flight time is less than 10 min.

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3.2 AERODYNAMIC COEFFICIENT DETERMINATION

At a typical point along the trajectory, tunnel parameters, balance forces and moments, and rig position are read into the computer and stored on magnetic tape. The balance loads are compared with stored balance limits, and the rig position is checked for coincidence with the previously commanded position. If this test fails, the limit is identified on the data tabulator, and the computer resets for another scan cycle. (It should be noted that the computer is not taken out of the control loop at any time during the trajectory; no action is required of the computer operator except loading the program before beginning the trajectory.) By repeating this data input-limit check cycle, the trajectory is not stopped because of spurious data inputs. If a limit is confirmed in consecutive cycles, the trajectory is terminated.

If the limits check satisfactorily, Fig. 10, the tunnel conditions are calculated using the standard Tunnel 4T data reduction program, and the balance inputs are converted to forces and moments using a standard six-component balance data reduction program. Finally, the measured forces and moments are shifted to the reference (full-scale) center-of-gravity location and corrected for static tares. Using these forces and moments and the tunnel dynamic pressure, the aerodynamic coefficients are then determined.

3.3 COEFFICIENT PREDICTION

The primary objective of the coefficient prediction technique is to minimize the tunnel test time required for a trajectory. Moving the rig in relatively large steps consumes less time than moving the same distance in several small steps. The coefficient prediction technique provides a means for adjusting the step size; small steps are taken in regions where the aerodynamic forces on the store are abruptly changing, and larger steps are made in regions where the aerodynamic forces are well behaved. Compared with the alternative method of taking more test points with a small fixed step size, the operating time is reduced by from 25 to 50 percent. By requiring the measured coefficient to fall within a prescribed band, this technique also serves as a rejection mechanism for spurious force data.

In the computation cycle (Fig. 10) the measured coefficients are compared with values previously predicted for this point. If this test fails, the trajectory data calculated in the previous computation cycle are discarded. If the comparison is satisfactory, the data are valid and define a point on the trajectory. These data are stored on magnetic tape, plotted on a cathode-ray-tube display, and tabulated on a line printer.

After a fixed number of consecutive successful predictions (typically six or eight), the length of the prediction interval is increased by a factor of 2 and following each missed prediction, the interval is decreased by a factor of 2, provided in each case that the prediction interval is within prescribed bounds. The interval length is bounded on the upper side by some arbitrary value which ensures that sufficient data points are taken along the trajectory. On the lower side, the interval cannot be smaller than the length of the integration interval used in solving the force and moment equations.

Note that there are two factors that influence the prediction accuracy: the width of the acceptable band within which the coefficients must fall and the minimum length of the prediction interval. The acceptance bandwidth cannot be made arbitrarily small since the balance data are repeatable only within finite limits; likewise, the minimum length of the prediction interval cannot be made arbitrarily large without compromising the accuracy of the trajectory data. Several missed predictions in a row indicate that the specified band is smaller than the repeatability of the balance dictates, or the minimum step size is too large. Conversely, no misses indicate that the acceptance band is too broad. A rule of thumb is to try to miss about ten percent of the points. Significantly more misses than this does not affect the trajectory, but does take more test time than necessary. Significantly fewer misses may indicate that the acceptance band is too wide to reject spurious balance data.

The predicted coefficient is simply a straight-line function of time. The values along this line are used to define the coefficient throughout the prediction interval. Following a good prediction, the slope of the coefficient-time line (Eq. (1)) is assumed to be the same as the measured slope of the preceding interval, and the beginning of the line is taken as the last measured value (Eq. (2)). This is not quite the same as saying that the assumed slope is unchanged from the previous cycle. By using only the measured values to define the predicted coefficients, random variations in the balance output are averaged out with fewer missed predictions.

$$K_x = (C_x - C_{x_j})/\Delta T_p \qquad (1)$$

$$C_{x_i} = C_x + K_{x_i} \Delta t \qquad (2)$$

where

$$x = N, Y, A, \ell, m, n$$

A missed prediction means that the coefficients used in determining the present position of the store were not correct; hence, the store is

not in the correct location. Therefore, the measured coefficients at this point are not too meaningful. After a bad prediction, the slope of the coefficient-time line for the next interval is assumed to be defined by this measured value and the second previous good value.

$$K_x = (C_x - C_{x_{j-1}})/(\Delta T_p + \Delta T_j)$$ (3)

Since the interval is reduced after each miss, the second previous good value is too remote to consider if there are two or more misses in a row. Therefore, for consecutive missed predictions, the slope is assumed to be given by the last measurement and the previous good measurement (Eq. (1)).

The choice of a linear coefficient rather than a constant, quadratic, or higher order fit was arbitrary. Ideally, a higher order function would produce a better fit, allowing larger steps. But since the present procedure is adequately productive (in most cases the store moves with maximum allowable step size along part of the trajectory), the linear coefficient method is considered adequate.

3.4 SOLUTION OF FULL-SCALE FORCE AND MOMENT EQUATIONS

The heart of the program is the integration loop. Reference 2 was used as a basis for the integration loop procedure. This loop operates on a small fixed time interval. A change in the prediction interval length merely changes the number of passes through this loop for a single prediction interval. By operating on a smaller time base than the prediction interval, the computational accuracy is enhanced; by operating with a fixed interval, the initial conditions for each data point are available from previous calculations. The numerical integration procedure uses position, velocity, and acceleration components from the past one or two calculations to define the present values. Unless a prediction has been missed, these initial conditions are updated with each pass through the calculations. After a missed prediction, all data stored in this loop are discarded and the integration cycle starts at exactly the same initial conditions that existed at the beginning of the previous integration cycle.

The integration loop equations are listed in Appendix II. Following the computation sequence through the integration loop, the rate of store rotation about the body axis is determined by integrating the angular acceleration components (Eqs. (II-1) to (II-3)). This velocity is transformed to a rate of change of the orientation angles and integrated again to produce the orientation (Eqs. II-4) to (II-9)). Translational velocity and the store center-of-gravity location are similarly determined (Eqs. (II-10) to (II-18)). The orientation angles correspond to the pitch-yaw-roll rotation sequence. That is, from an initial alignment of body axis

and tunnel axis, an arbitrary body axis orientation is presumed to be obtained by pitching through the angle ν; then yawing through the angle η, and finally rolling through the angle ω, see Fig. 11. This sequence serves to define the matrix for transforming vectors from tunnel axis to body axis and vice versa, see Ref. 3.

· The full-scale force and moment equations (Eqs. (II-28) to (II-33)) include store weight components (Eqs. (II-19) to (II-21)), specified forcing functions to simulate launch forces and store thrust (Eqs. (II-22) to (II-25)), and aerodynamic forces, see Fig. 12. In addition to the aerodynamic coefficients, various damping coefficients may be specified. The damping coefficients generally represent a second order of magnitude in the total moment exhibited by the store, and the accuracy with which the damping coefficients have to be estimated is not too critical. However, if the store model experiences rather large oscillatory motion, an additional test run should be made with a significant change in the damping coefficients to ascertain the effect of the damping moment components on the trajectory. The force and moment equations in their present form are sufficiently general to handle most situations. The tremendous flexibility provided by the digital computer permits modifications as required.

The rigid body equations of motion (Ref. 3, assuming an xz-plane of symmetry) are finally solved for the store body axis acceleration components (Eqs. (II-34) to (II-39)) to conclude the calculations for a single integration interval. Time is then advanced by the length of this interval, and the integration process is repeated until the end of the prediction interval is reached.

3.5 OUTPUT CALCULATIONS

Having calculated the location of the full-scale store center of gravity and the orientation of the store body axes, it remains to convert these to model scale in rig coordinates. The orientation angles calculated in the integration loop may be transferred directly to the rig after correcting for deflection.

$$\nu_R = \nu_p - \Delta\nu \tag{4}$$

$$\eta_R = \eta_p - \Delta\eta \tag{5}$$

$$\omega_R = \omega_p - \Delta\omega \tag{6}$$

The correction for sting deflection is determined from the last measured forces and moments. As this correction is applied at the following store location, the deflection correction is lagging by one point. Since

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the deflection is small, the point-to-point change may be neglected. The deflection of the rig caused by aerodynamic loads acting on the model support head, transverse horizontal wing, and vertical strut was monitored during the first few tests and found to be negligible.

A geometric correction must be applied to the translational coordinates found in the integration loop, since the center of rotation of the rig does not correspond to the center of gravity of the model, see Fig. 2.

$$X_R = X_{R1} + 12\lambda x_p + (\ell_1 + 3) - (\ell_1 \cos \eta_R + 3) \cos \nu_R + d \sin \nu_R \qquad (7)$$

where

$$d = \begin{cases} 6, & \text{with roll axis offset} \\ 0, & \text{without offset} \end{cases}$$

$$Y_R = Y_{R1} + 12\lambda y_p - \ell_1 \sin \eta_R \qquad (8)$$

$$Z_R = Z_{R1} + 12\lambda z_p + (\ell_1 \cos \eta_R + 3) \sin \nu_R - d(1 - \cos \nu_R) \qquad (9)$$

The translational and rotational coordinates of the rig are finally compared with the rig travel limits, Fig. 10, before being output to the DAC. The trajectory is terminated when one of these limits is reached.

3.6 SOURCES OF ERROR

Although the effects of the various inaccuracies cannot be quantitatively stated for the general case, some of the sources of error that can contribute to deviations of the wind tunnel trajectory from the free-flight trajectory may be noted.

1. Model inaccuracies. In addition to errors resulting from an inadequate definition of the forces and moments acting on the full-scale store (Eqs. (II-19) to (II-33)) and interference caused by the presence of the support system, there are inherent errors associated with captive-trajectory testing. The basic assumption in the wind tunnel tests is that the flow field of the parent aircraft is the same in the wind tunnel as in free flight. But any flow field disturbance resulting from store acceleration is not simulated since it is physically impossible to duplicate a velocity difference between parent and store in the wind tunnel. Also, disturbances such as parent wing deflection resulting from store launch cannot be simulated.

2. Measurement inaccuracies. Depending primarily on the magnitude of the forces and moments measured on the model, the uncertainty

of the balance measurements may be from a fraction of a per-
cent to a significant fraction of the measured value. However,
a large uncertainty band does not preclude obtaining a credible
trajectory. Since many data points are taken, random fluctua-
tions are very effectively averaged in the double integration
processing that occurs between force measurement and store
positioning. Moreover, since a large uncertainty is usually
associated with a small measurement amplitude, the resulting
motion will usually be small - however imprecise. But this
is not saying that significant errors cannot creep in. For
instance, a balance zero shift would appear as an offset in
acceleration which would not be averaged out.

Since the coefficients usually vary much more strongly with
orientation than displacement, the moment measurements
potentially represent the greatest source of error. To a first
approximation the angular acceleration is given by the ratio of
moment to moment of inertia ($\dot{p} - \ell/I_x$). Because the full-scale
moments are primarily determined from model measurements
(except possibly for a pitching moment imposed at launch, see
Eqs. (II-31) to (II-33)), the combination of an imprecise moment
measurement with a small moment of inertia may produce a
significant acceleration error, and hence uncertain trajectories.

3. Positioning inaccuracies. As previously noted, the positioning
   accuracy is within 0.2 percent of full-scale travel of the CTS.
   This corresponds to defining the position of the full-scale store
   within a few inches and the angular orientation within a degree
   or so at most.

4. Calculation inaccuracies. Aside from the errors in the
   coefficient-time approximations (which are just a reflection of
   the balance measurement uncertainties), the computations may
   by considered precise. The round-off error is negligible since
   the computer has a 24-bit word length. Any error introduced in
   the numerical integration should be insignificant after a few
   points since the procedure provides the accuracy of a quadratic
   fit over every Δt interval.

SECTION IV
CONCLUDING REMARKS

The wind tunnel provides an accurate simulation of the parent-store
flow field for a wide range of flight conditions. The laws of motion

governing the behavior of the store include many parameters that are not flow field dependent. Hence for a given parent-store geometric configuration, the influence on the store separation characteristics can be rapidly assessed. Typical studies may include:

1. Variation of ejection forces. Both the force-time history and the location of the ejection stations can be varied.

2. Variation of store thrust. The effects of varying both the delay time from store release to ignition and the thrust-time history can be evaluated.

3. Variation of store center of gravity location.

4. Variation of damping coefficients.

5. Variation of release attitude. Release may be simulated at any arbitrary orientation of parent, i.e., in a climb, dive, or roll attitude.

6. Variation of simulated altitude. Assuming aerodynamic forces vary directly with dynamic pressure, the model measurement can be scaled to altitude conditions outside the operating range of the tunnel.

Captive trajectory testing provides a wide spectrum of simulation possibilities in addition to the usual wind tunnel variables of Mach number, dynamic pressure, angle of attack, and varying geometric configuration.

The speed and precision of the CTS position control promotes its use for nontrajectory tests also. A sequence of positions can be rapidly traversed (computer entry from punched cards) with the desired data collected at each point. Typical uses to date include:

1. Grid test. The store model is located at various positions and attitudes relative to the parent, forces and moments measured and aerodynamic coefficients calculated and displayed.

2. Free air test. The store model, with no parent present, is rotated in pitch, yaw, and/or roll and data are reduced as in the grid test.

3. Flow field survey. A pressure probe mounted on the CTS rig is used to map any region of interest.

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        Tunnel Facility, Vol. 5." Arnold Engineering Development
        Center, July 1968.

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        of Stores Launched from Aircraft." Report 1878 (AD612515),
        David Taylor Model Basin, November 1964.

3. Thelander, J. A. "Aircraft Motion Analysis." FDL-TDR-64-70,
        March 1965.
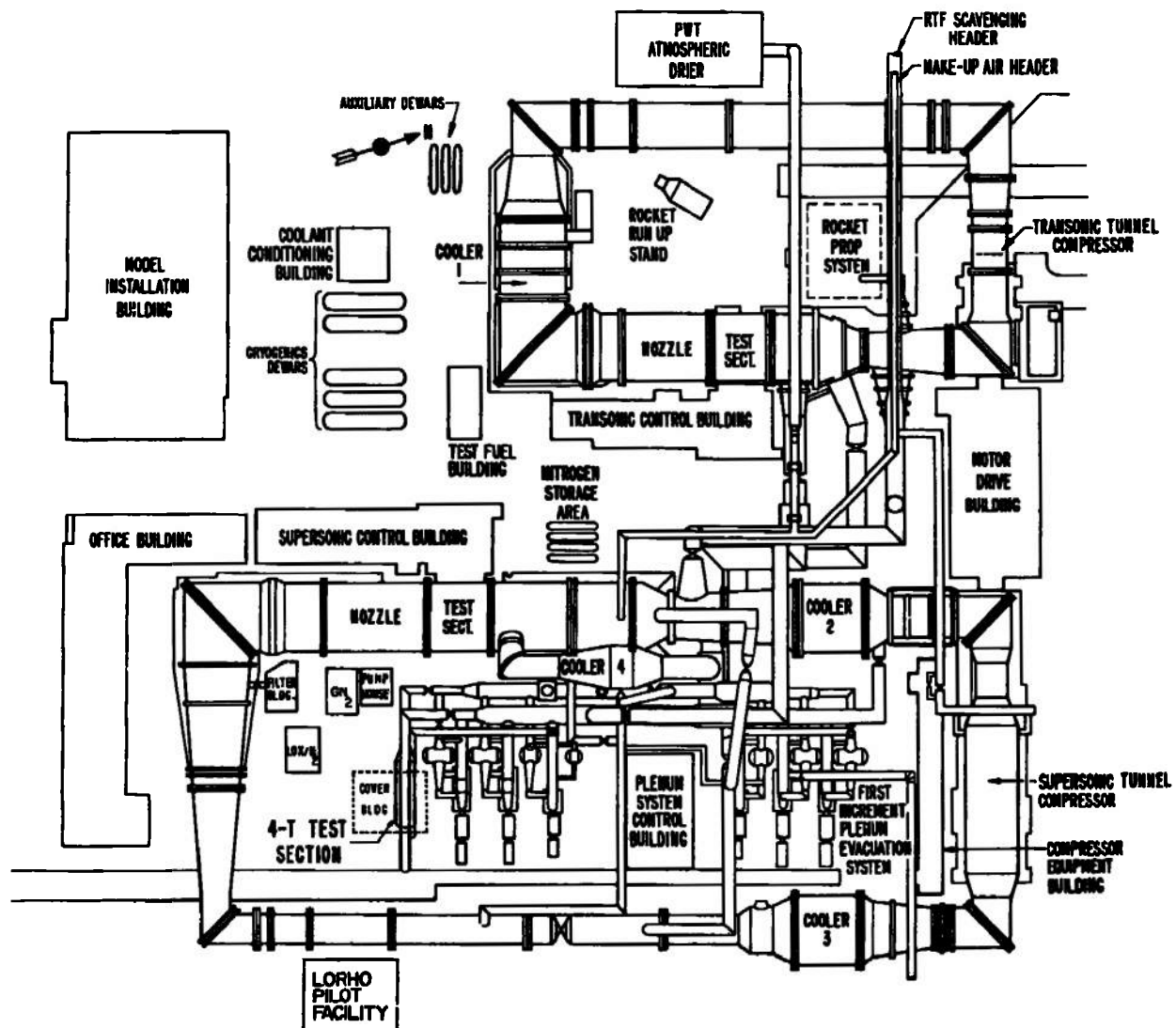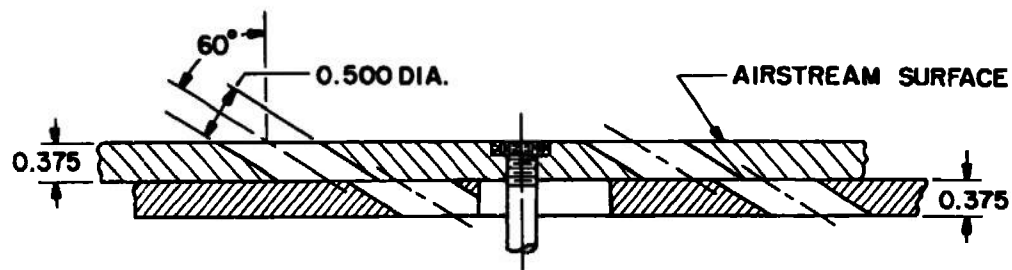
APPENDIXES
I. ILLUSTRATIONS
II. INTEGRATION LOOP EQUATIONS

Fig. 1 PWT Facility Layout

60°

0.500 DIA.

AIRSTREAM SURFACE

NOTES:

1. TUNNEL STATIONS AND DIMENSIONS IN INCHES

2. CTS RIG SHOWN AT CENTER OF TRAVEL

0.375

0.375

TYPICAL PERFORATED WALL CROSS SECTION

SOLID AREAS

PERFORATED WALLS (6.0% MAXIMUM OPEN AREA)

STA. 133.25
CTS PITCH
CENTER

FLOW
EXPANSION
REGION

ℓ_1

DIFFUSER

STA.
0.0

STA.
72.0

REFERENCE
CENTER
OF
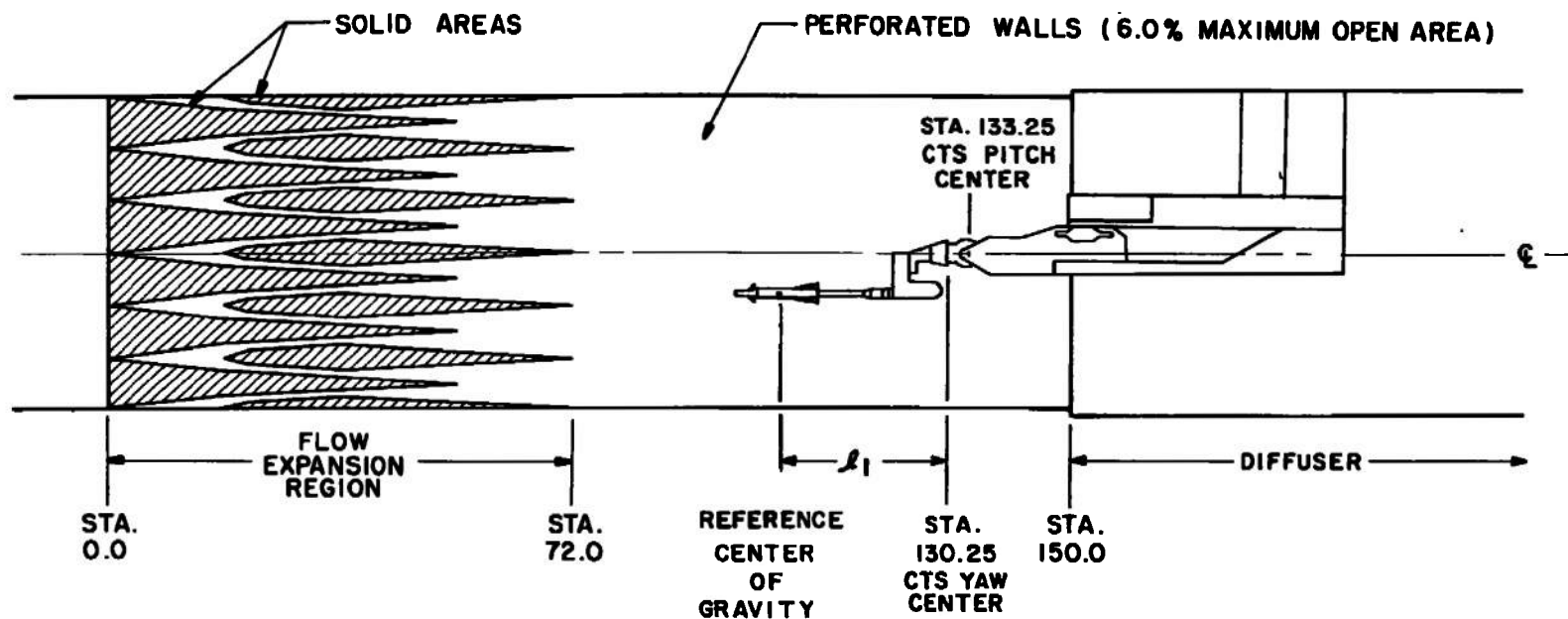GRAVITY

STA.
130.25
CTS YAW
CENTER

STA.
150.0

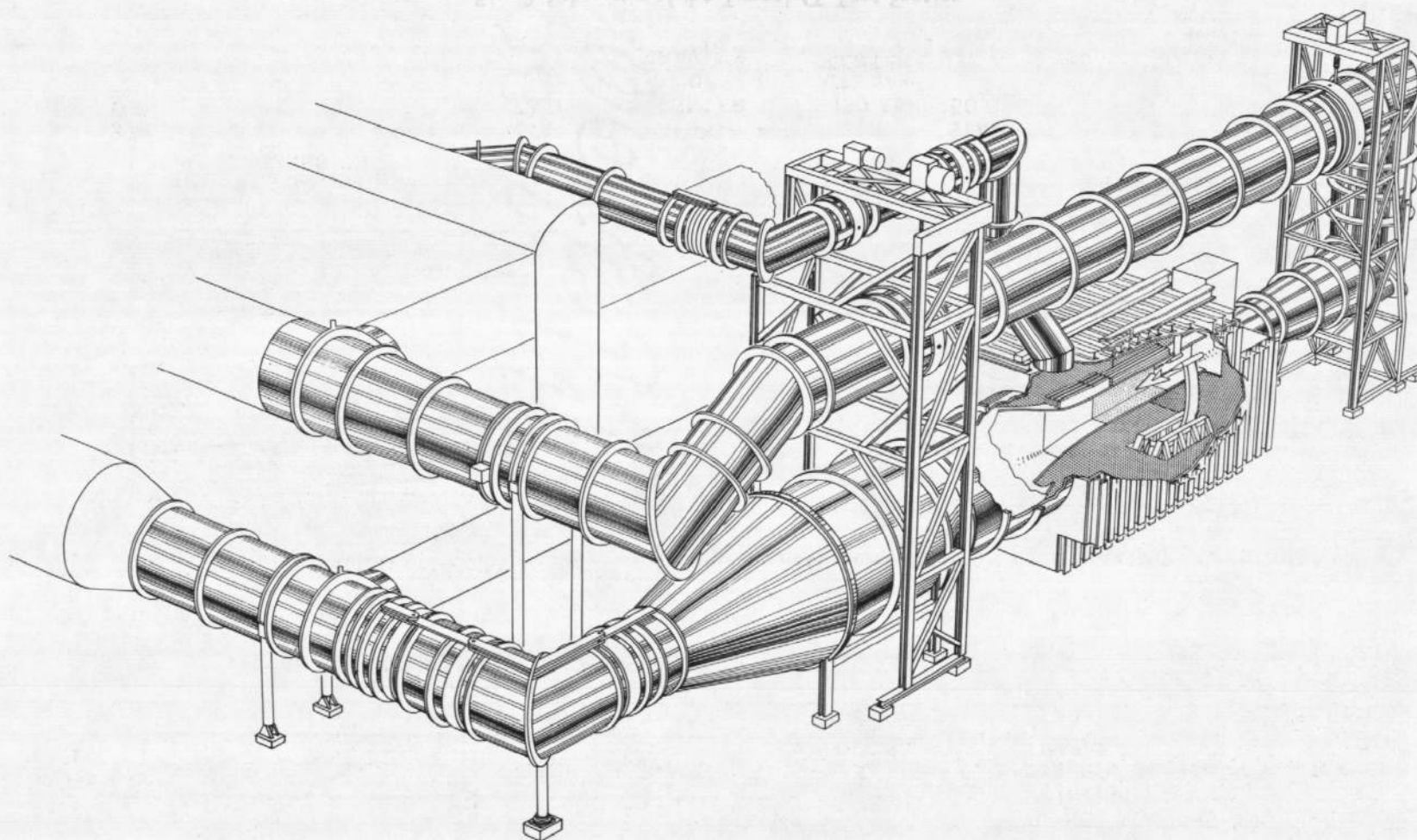Fig. 2 Schematic of the Tunnel 4T Test Section
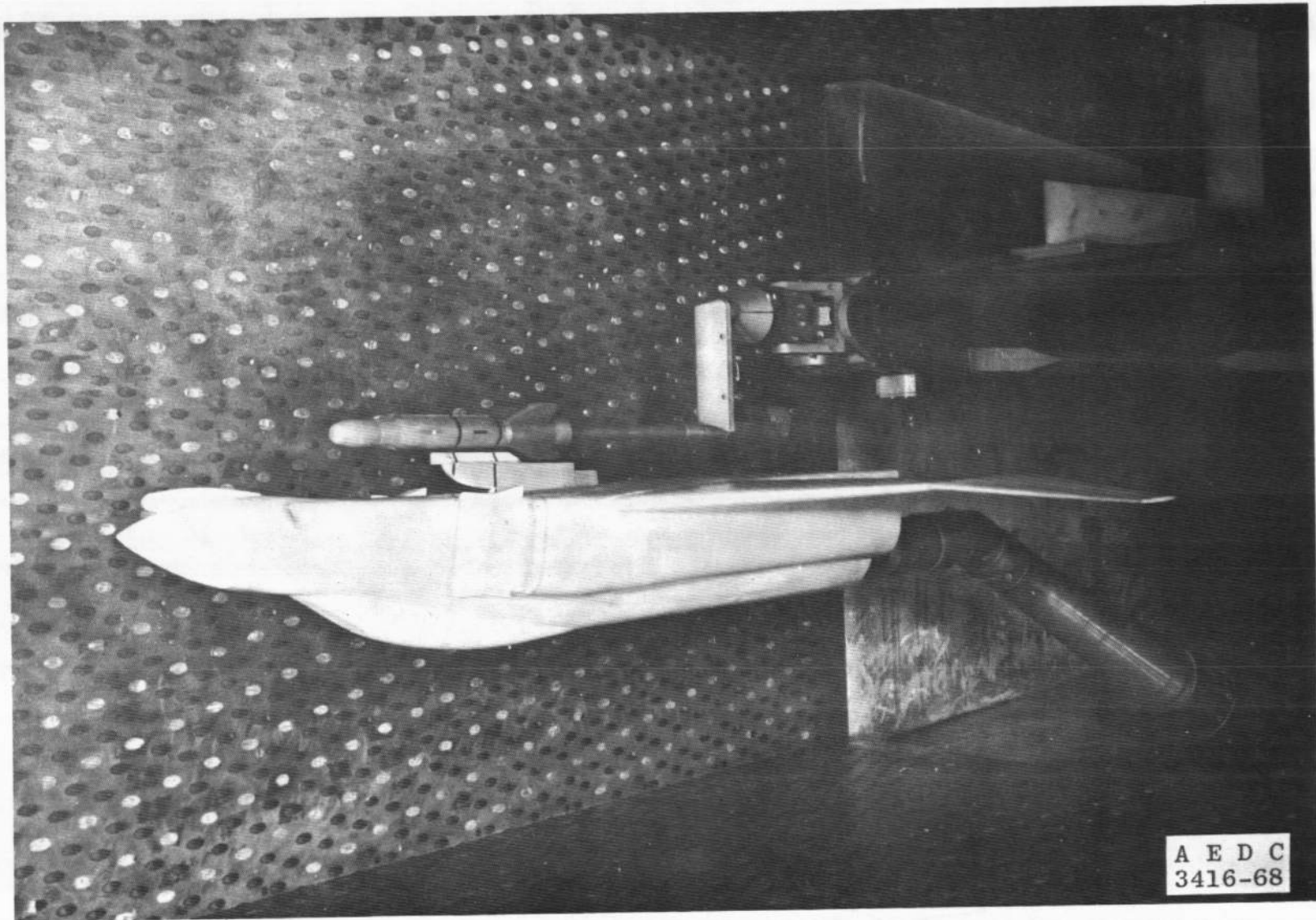
Fig. 3 Tunnel 4T General Arrangement

Fig. 4 Photograph of a Typical CTS Installation

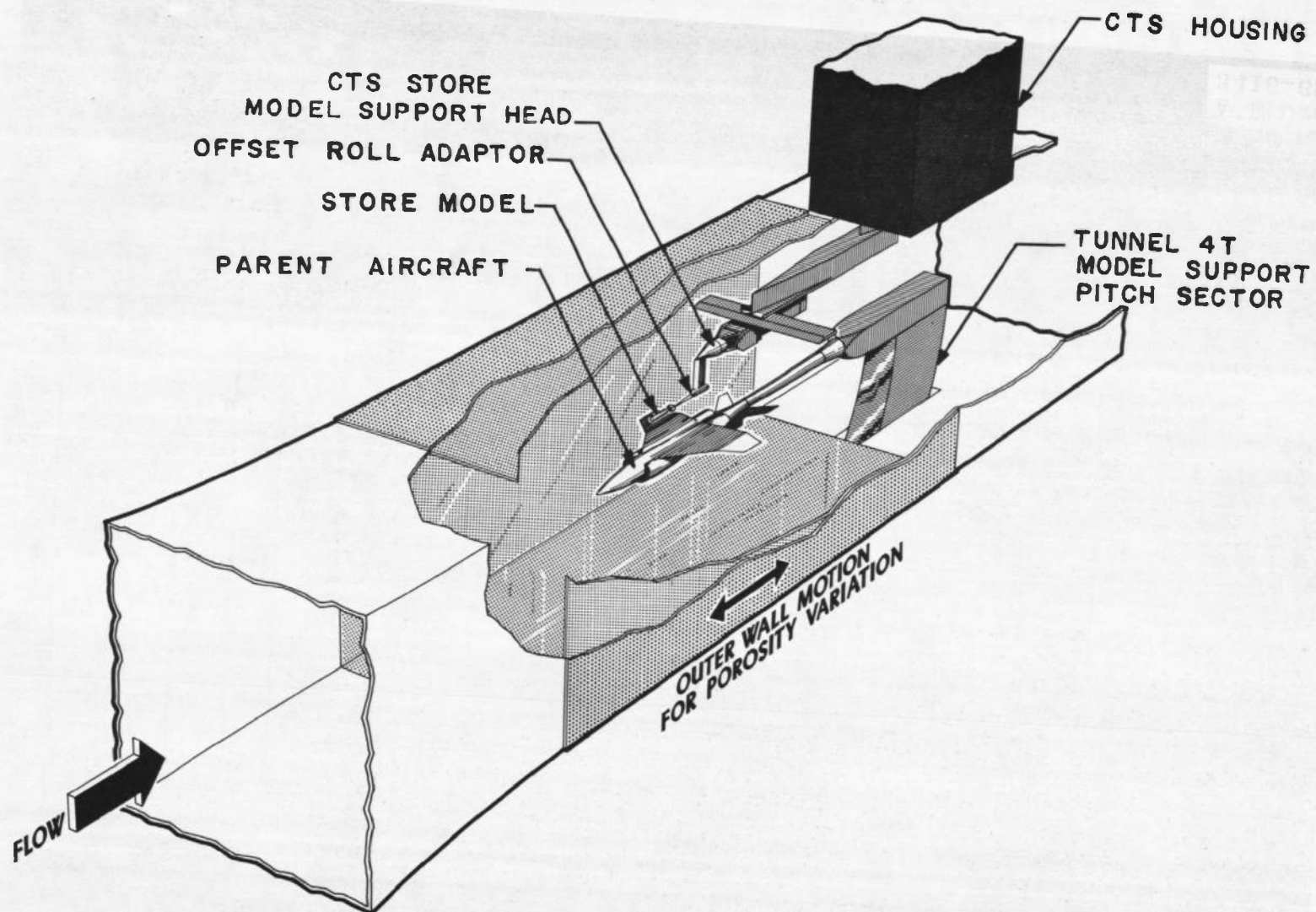Fig. 5 Isometric Drawing of the CTS and Tunnel 4T Test Leg

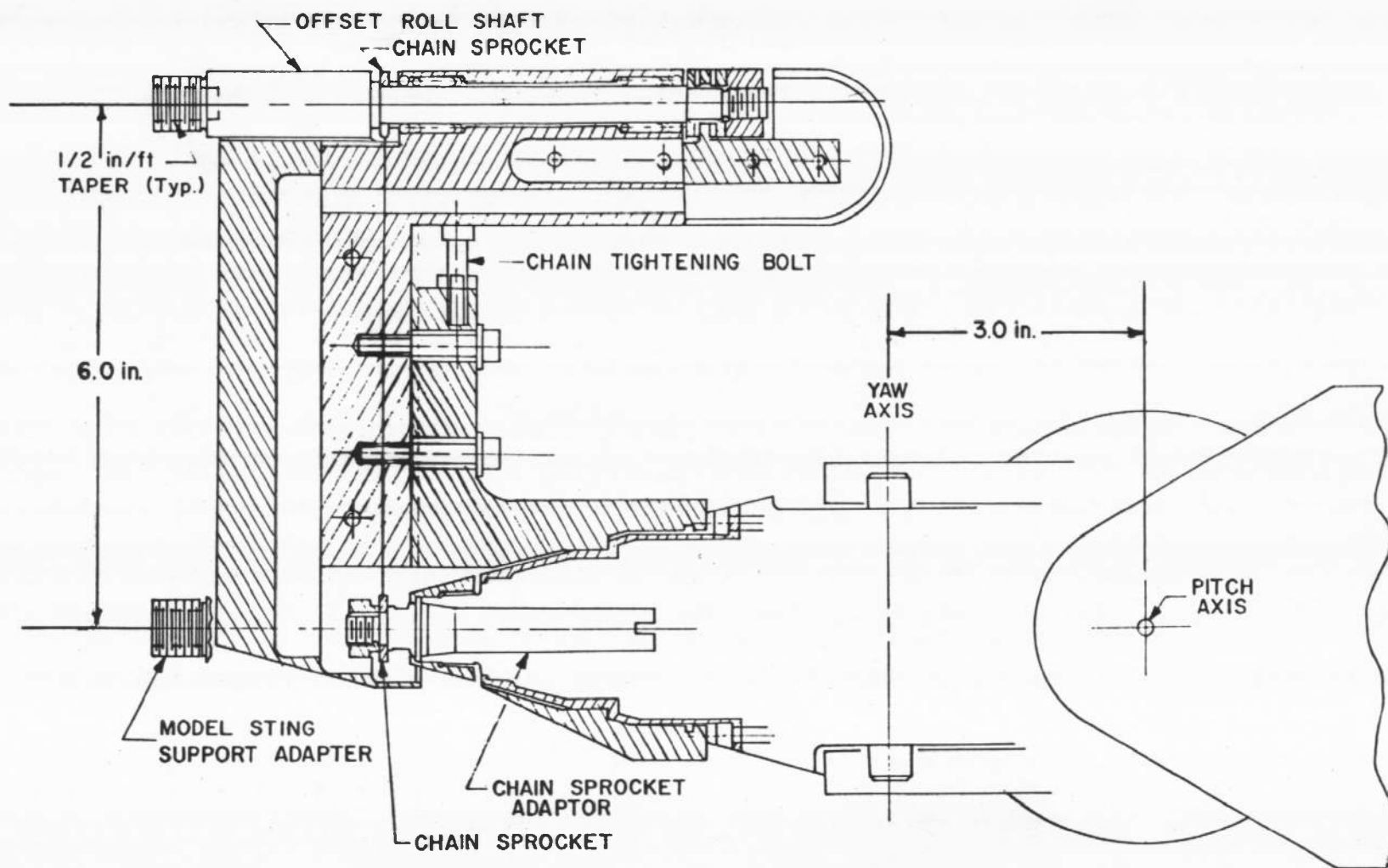CTS HOUSING

CTS STORE
MODEL SUPPORT HEAD

OFFSET ROLL ADAPTOR

STORE MODEL

PARENT AIRCRAFT

TUNNEL 4T
MODEL SUPPORT
PITCH SECTOR

OUTER WALL MOTION
FOR POROSITY VARIATION

FLOW

Fig. 6 Detail of the CTS Model Support Head and Store Roll Provisions

THESE COMPONENTS
LOCATED INSIDE TUNNEL

MANUAL
INPUTS

STORE SEPARATION
DRIVE SYSTEM

CONTROLLER

OPERATIONAL
AMPLIFIER

FEEDBACK

POSITION
INDICATOR

BALANCE

FORCES
AND
MOMENTS

RAYTHEON
520
COMPUTER

X   Y   Z   υ η ω

SIGNAL
CONDITIONING

DIGITAL TO
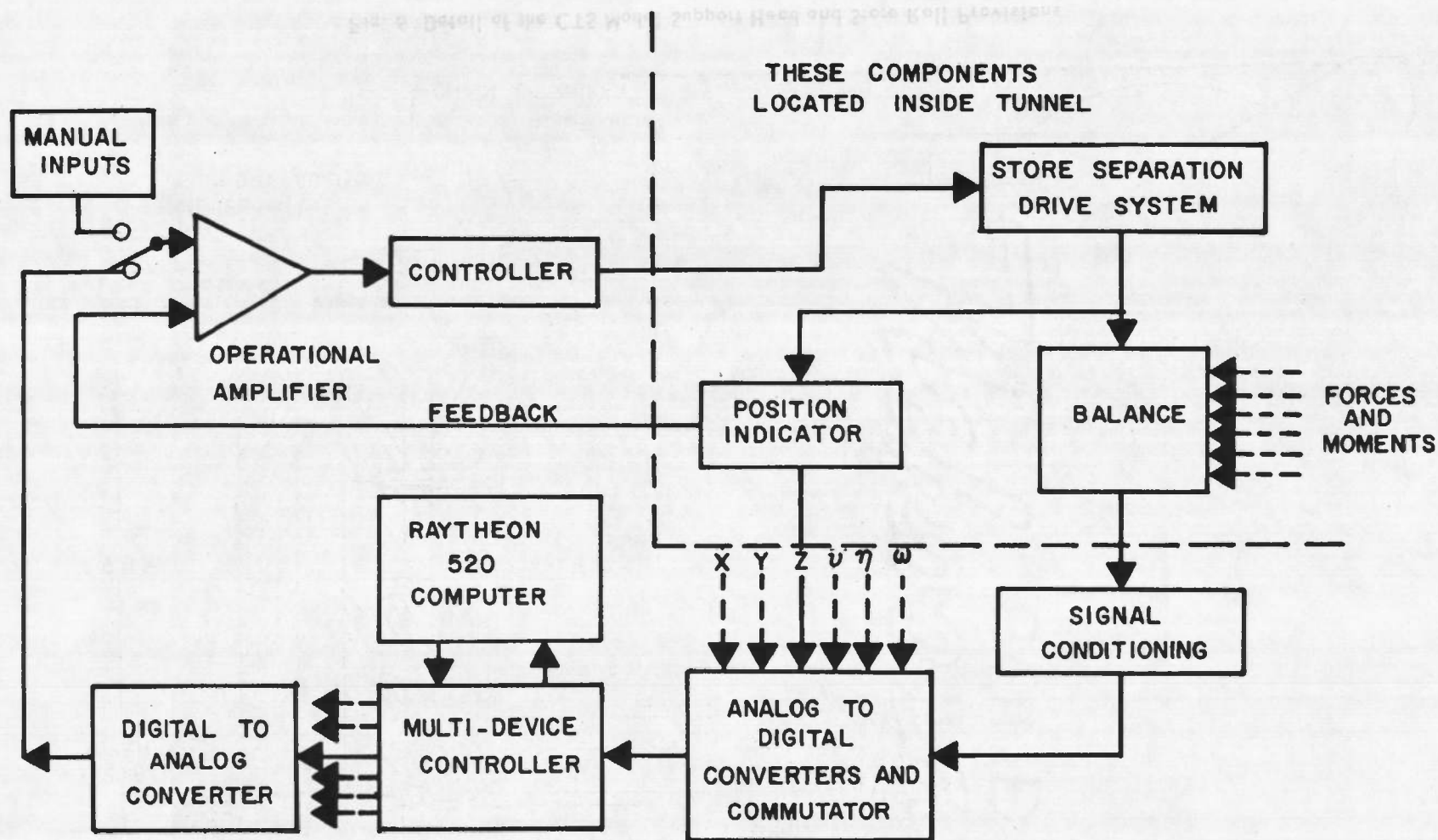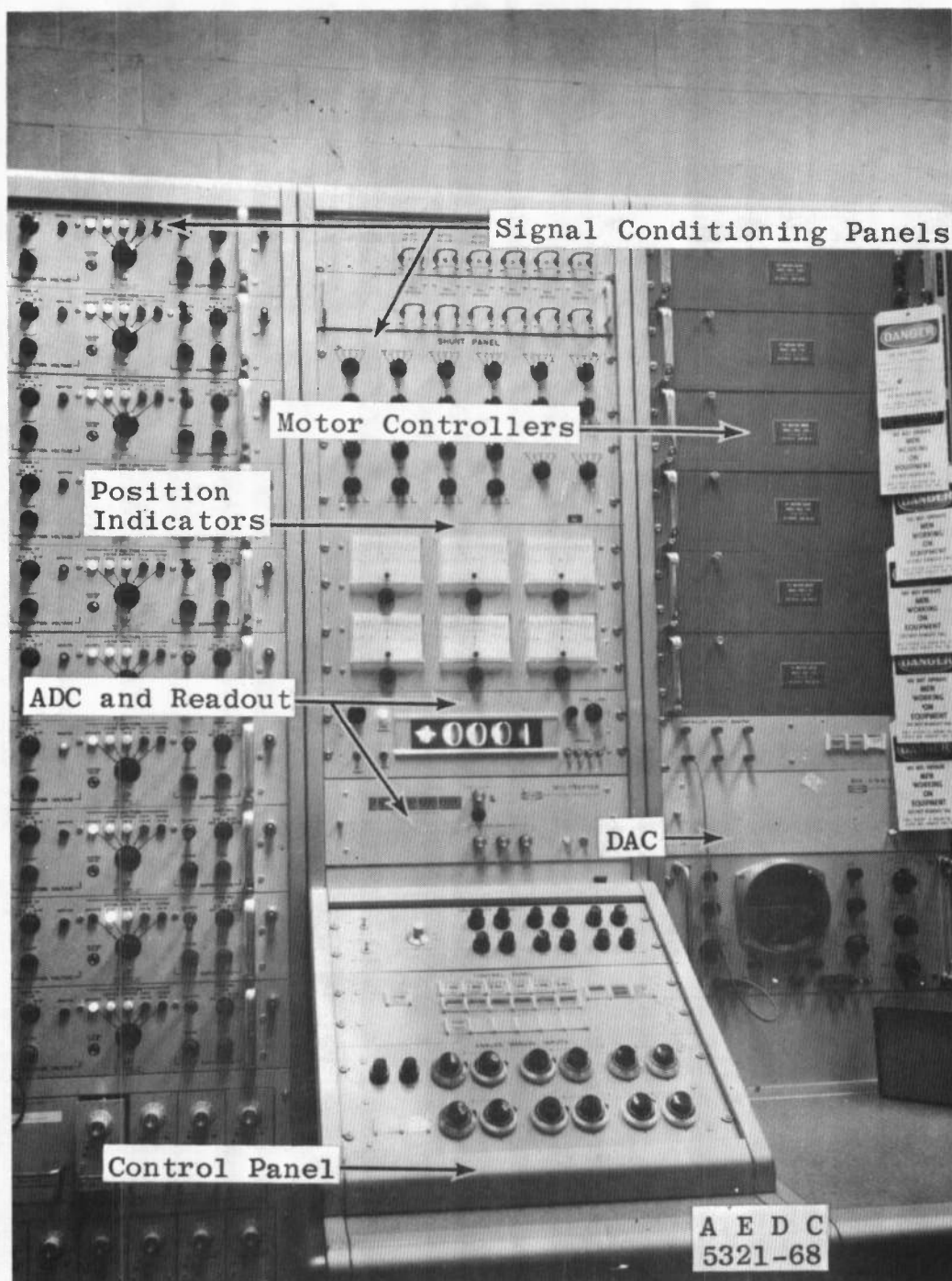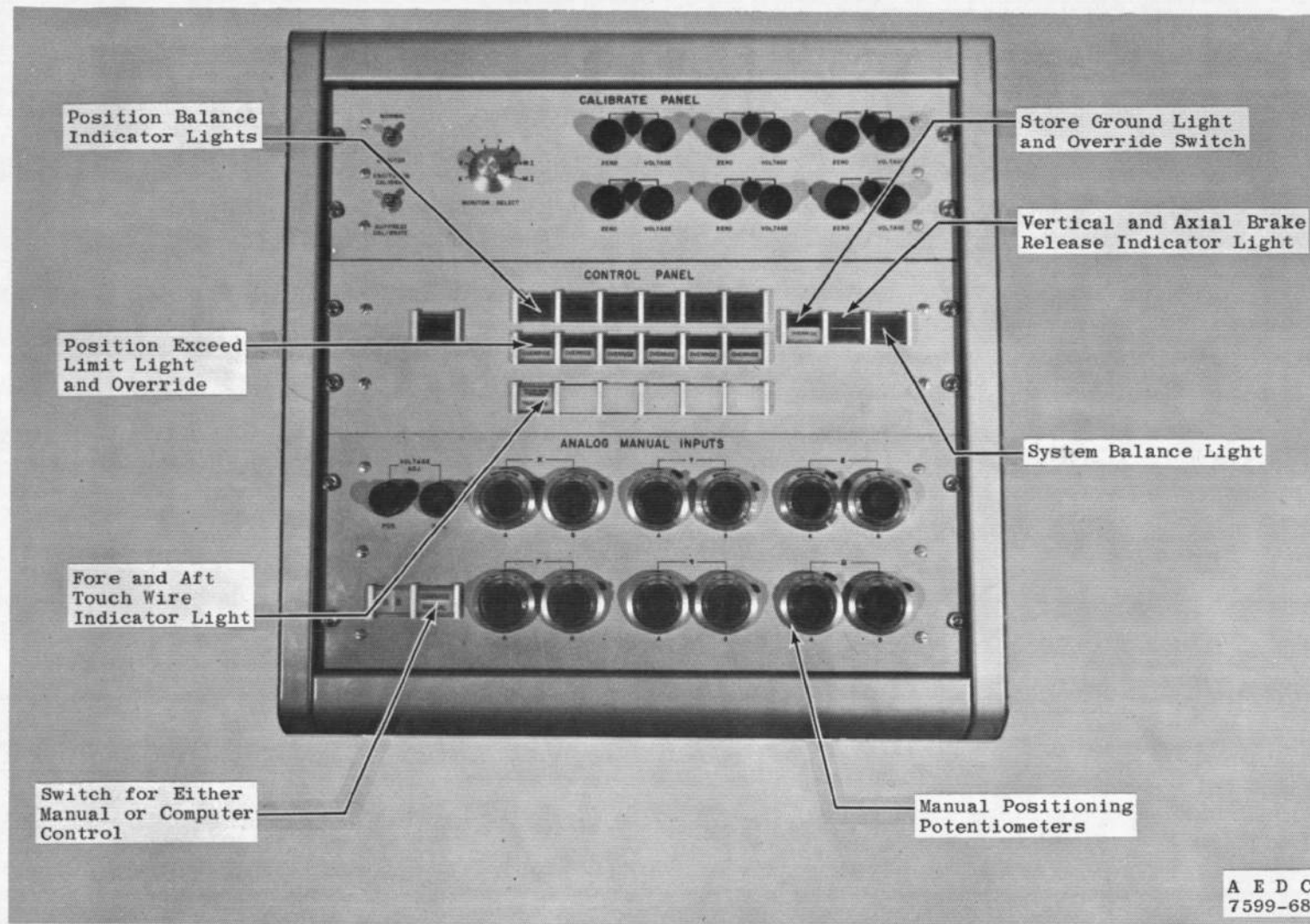ANALOG
CONVERTER

MULTI-DEVICE
CONTROLLER

ANALOG TO
DIGITAL
CONVERTERS AND
COMMUTATOR

Fig. 7 Schematic of CTS Control System

a. Control Console Components
Fig. 8 Photograph of the CTS Control Console

Position Balance
Indicator Lights

Store Ground Light
and Override Switch

Vertical and Axial Brake
Release Indicator Light

Position Exceed
Limit Light
and Override

System Balance Light

Fore and Aft
Touch Wire
Indicator Light

Switch for Either
Manual or Computer
Control

Manual Positioning
Potentiometers

CALIBRATE PANEL

CONTROL PANEL

ANALOG MANUAL INPUTS

AEDC
7599-68

b. Control Panel Components
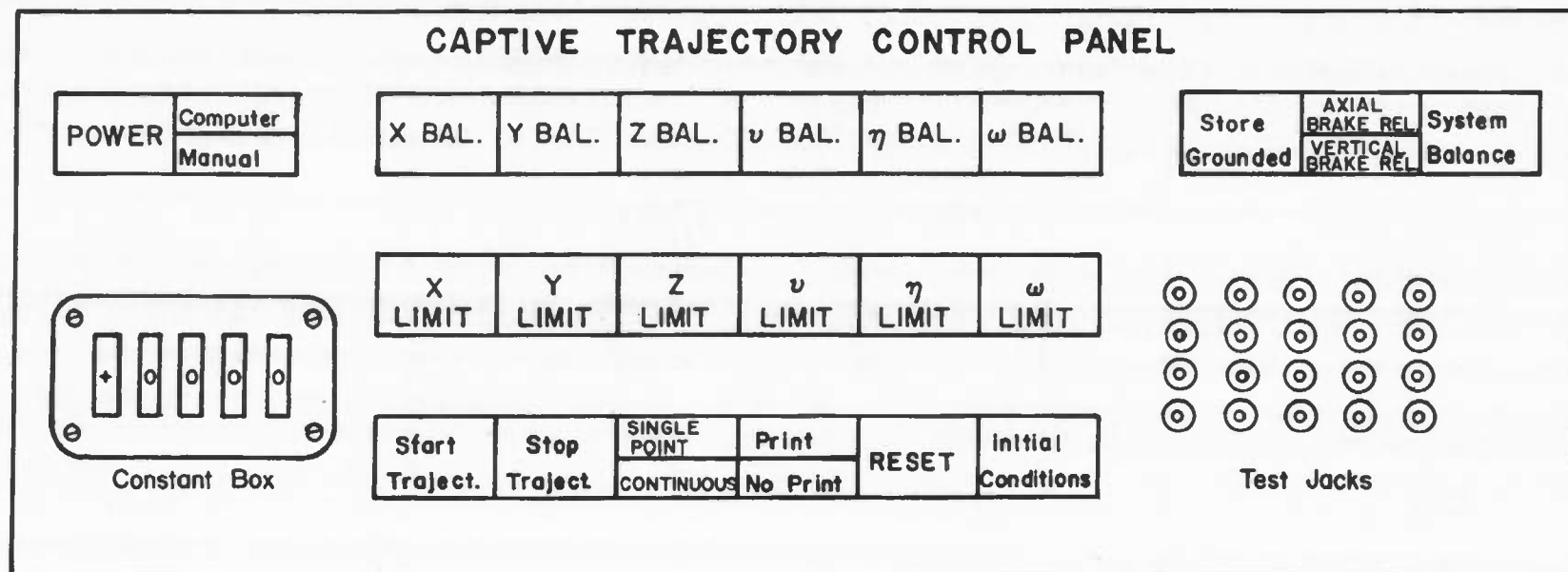
Fig. 8 Concluded

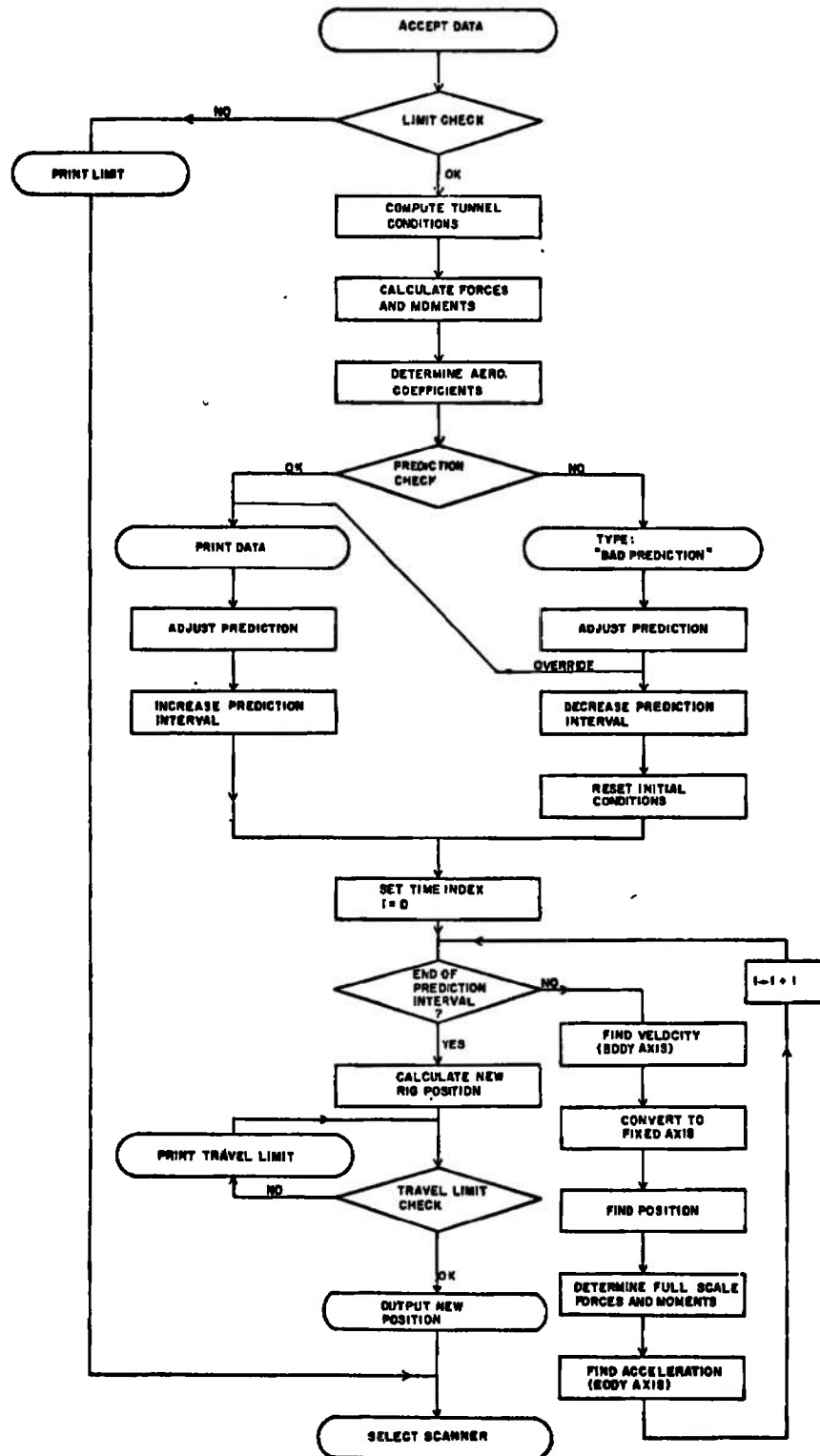Fig. 9 Layout of CTS Control Panel Located on Tunnel 4T Control Console
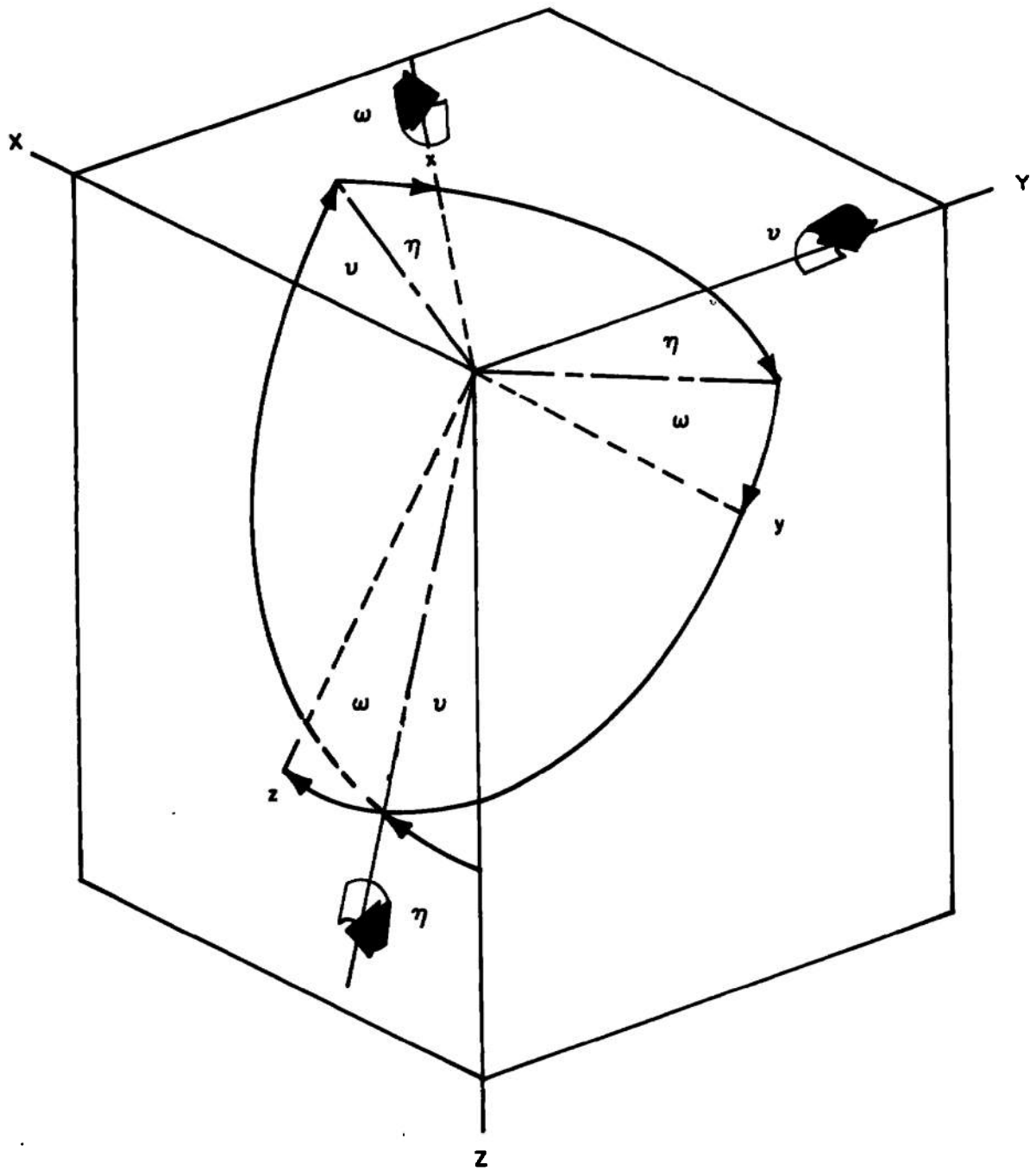
Fig. 10 Trajectory Generation Flow Diagram

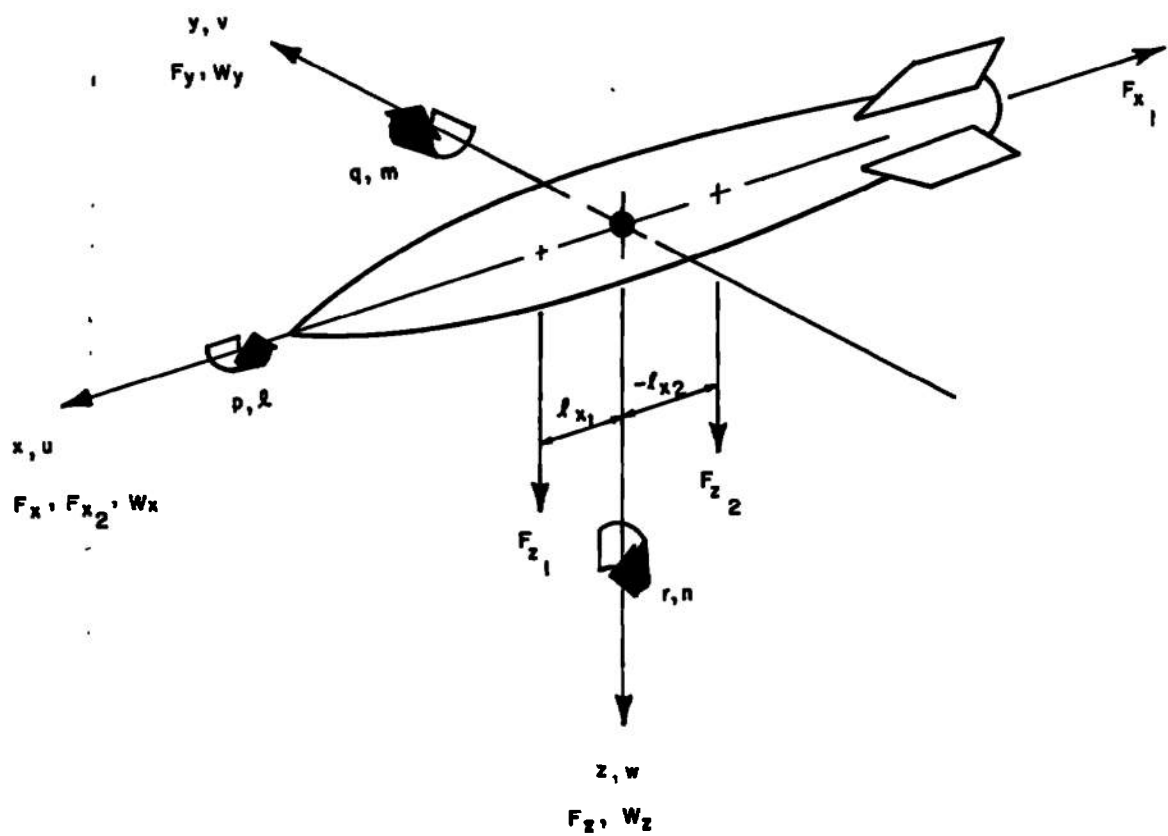27

Fig. 11 The Pitch-Yaw-Roll Rotation Sequence

Fig. 12 Body Axis

APPENDIX II
INTEGRATION LOOP EQUATIONS

ROTATIONAL VELOCITY AND ORIENTATION

$$p_i = p_{i-1} + (3\dot{p}_{i-1} - \dot{p}_{i-2})\ \Delta t/2 \qquad (II-1)$$

$$q_i = q_{i-1} + (3\dot{q}_{i-1} - \dot{q}_{i-2})\ \Delta t/2 \qquad (II-2)$$

$$r_i = r_{i-1} + (3\dot{r}_{i-1} - \dot{r}_{i-2})\ \Delta t/2 \qquad (II-3)$$

$$\dot{\eta}_i = r_i\ \cos\ \omega_{i-1} + q_i\ \sin\ \omega_{i-1} \qquad (II-4)$$

$$\eta_i = \eta_{i-1} + (\dot{\eta} + \dot{\eta}_{i-1})\ \Delta t/2 \qquad (II-5)$$

$$\dot{\nu}_i = (q_i\ \cos\ \omega_{i-1} - r_i\ \sin\ \omega_{i-1})\ /\cos\ \eta_i \qquad (II-6)$$

$$\nu_i = \nu_{i-1} + (\dot{\nu}_i + \dot{\nu}_{i-1})\ \Delta t/2 \qquad (II-7)$$

$$\dot{\omega}_i = p_i - \dot{\nu}_i\ \sin\ \eta_i \qquad (II-8)$$

$$\omega_i = \omega_{i-1} + (\dot{\omega}_i + \dot{\omega}_{i-1})\ \Delta t/2 \qquad (II-9)$$

TRANSLATIONAL VELOCITY AND POSITION

$$u_i = u_{i-1} + (3\dot{u}_{i-1} - \dot{u}_{i-2})\ \Delta t/2 \qquad \text{(II-10)}$$

$$v_i = v_{i-1} + (3\dot{v}_{i-1} - \dot{v}_{i-2})\ \Delta t/2 \qquad \text{(II-11)}$$

$$w_i = w_{i-1} + (3\dot{w}_{i-1} - \dot{w}_{i-2})\ \Delta t/2 \qquad \text{(II-12)}$$

$$\begin{bmatrix} \dot{X}_i \\[6pt] \dot{Y}_i \\[6pt] \dot{Z}_i \end{bmatrix} = [A] \begin{bmatrix} u_i \\[6pt] v_i \\[6pt] w_i \end{bmatrix}$$

$$\text{(II-13)}$$
$$\text{(II-14)}$$
$$\text{(II-15)}$$

where

$$[A] = \begin{bmatrix} \cos \nu \ \cos \eta & \sin \eta & -\sin \nu \ \cos \eta \\[6pt] \begin{array}{l} \sin \omega \ \sin \nu \\ -\cos \omega \ \cos \nu \ \sin \eta \end{array} & \cos \omega \ \cos \eta & \begin{array}{l} \sin \omega \ \cos \nu \\ +\cos \omega \ \sin \nu \ \sin \eta \end{array} \\[12pt] \begin{array}{l} \cos \omega \ \sin \nu \\ +\sin \omega \ \cos \nu \ \sin \eta \end{array} & -\sin \omega \ \cos \eta & \begin{array}{l} \cos \omega \ \cos \nu \\ -\sin \omega \ \sin \nu \ \sin \eta \end{array} \end{bmatrix}$$

$$X_i = X_{i-1} + (\dot{X}_i + \dot{X}_{i-1})\ \Delta t/2 \qquad \text{(II-16)}$$

$$Y_i = Y_{i-1} + (\dot{Y}_i + \dot{Y}_{i-1})\ \Delta t/2 \qquad \text{(II-17)}$$

$$Z_i = Z_{i-1} + (\dot{Z}_i + \dot{Z}_{i-1})\ \Delta t/2 \qquad \text{(II-18)}$$

STORE WEIGHT

$$
\begin{bmatrix} w_x \\ w_y \\ w_z \end{bmatrix} = [A]' \begin{bmatrix} w_X \\ w_Y \\ w_Z \end{bmatrix}
$$

(II-19)

(II-20)

(II-21)

where $[A]'$ is the transpose of $[A]$

APPLIED FORCES

$$
F_{x_1} = \begin{cases} a_0 + a_1 t + a_2 t^2 + \ldots + a_5 t^5, & t \le a_t \\ 0, & t > a_t \end{cases}
$$

(II-22)

$$
F_{x_2} = \begin{cases} b_0 + b_1 t + \ldots + b_5 t^5, & t \le b_t \\ 0, & t > b_t \end{cases}
$$

(II-23)

$$
F_{z_1} = \begin{cases} c_0 + c_1 t + \ldots + c_5 t^5, & t \le c_t \\ 0, & t > c_t \end{cases}
$$

(II-24)

$$
F_{z_2} = \begin{cases} d_0 + d_1 t + \ldots + d_5 t^5, & t \le d_t \\ 0, & t > d_t \end{cases}
$$

(II-25)

TOTAL VELOCITY

$$
U_i = \left[(U_i + \dot{X}_i)^2 + \dot{Y}_i^2 + \dot{Z}_i^2 \right]^{1/2}
$$

(II-26)

STORE DYNAMIC PRESSURE

$$
q_s = \lambda_\rho \rho_1 U_i^2 / 2
$$

(II-27)

FULL-SCALE FORCES AND MOMENTS

$$F_x = W_x - q_sS\,C_{A_i} - F_{x_1} + F_{x_2} \qquad\qquad \text{(II-28)}$$

$$F_y = W_y + q_sS\,C_{Y_i} \qquad\qquad \text{(II-29)}$$

$$F_z = W_z - q_sS\,C_{N_i} + F_{z_1} + F_{z_2} \qquad\qquad \text{(II-30)}$$

$$\ell = q_sSb\left[C_{\ell_i} + C_{\ell p}\,(bp_i/2U_i)\right] \qquad\qquad \text{(II-31)}$$

$$m = q_sS\bar{c}\left[C_{m_i} + C_{mq}\,(\bar{c}q_i/2U_i)\right] - F_{z_1}\ell_{x1} - F_{z_2}\ell_{x2} \qquad \text{(II-32)}$$

$$n = q_sSb\left[C_{ni} + C_{nr}\,(br_i/2U_i)\right] \qquad\qquad \text{(II-33)}$$

STORE ACCELERATION

$$\dot{u}_i = (F_x/\bar{m}) + r_iv_i - q_iw_i \qquad\qquad \text{(II-34)}$$

$$\dot{v}_i = (F_y/\bar{m}) + p_iw_i - r_iu_i \qquad\qquad \text{(II-35)}$$

$$\dot{w}_i = (F_z/\bar{m}) + q_iu_i - p_iv_i \qquad\qquad \text{(II-36)}$$

$$\dot{p}_i = \dot{p}_{ni} + \dot{r}_{ni}(I_{xz}/I_x) / \left[1 - (I_{xz}^2/I_xI_z)\right] \qquad\qquad \text{(II-37)}$$

where

$$\dot{p}_{ni} = \left[\ell - q_ir_i(I_z - I_y) + p_iq_iI_{xz}\right]/I_x$$

$$\dot{r}_{ni} = \left[n - q_ir_i\,I_{xz} - p_iq_i(I_y - I_x)\right]/I_z$$

$$\dot{q}_i = \left[m \quad - \quad (p_i^2 - r_i^2)I_{xz} - p_i r_i (I_x - I_z) \right] / I_y \qquad \text{(II-38)}$$

$$\dot{r}_i = \left[n \quad + \quad (\dot{p}_i - q_i r_i)I_{xz} - p_i q_i (I_y - I_x) \right] / I_z \qquad \text{(II-39)}$$

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13. ABSTRACT

The captive-trajectory store-separation system of the AEDC Aerodynamic Wind Tunnel, Transonic (4T), provides the capability for determining the separation trajectory of a store in the vicinity of the parent aircraft. This system may also be used as a six-degree-of-freedom support for conventional force tests with or without a parent installed, and as a pressure probe or transducer mounting platform for flow field surveys in the vicinity of a model. With the store and parent independently supported in the tunnel, trajectory generation involves measurement of forces and moments acting on the captive store model, converting these to full-scale, adding other forces and moments which may be applied to the full-scale store, solving the equations of motion for store acceleration, integrating these equations to find store displacement, converting this movement to model scale, and physically moving the store model along its flight path. This report describes the captive-trajectory store-separation system and its testing capabilities and presents the technique used for trajectory generation.

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stores, aircraft						
separation characteristics						
transonic flow						
trajectory generation						

1. Stores -- Separation
-- Trajectories
2. " "
3. Transonic wind tunnels -- PWT (4T)
4 Trajectories

1-2